Modifying WRF's Radiation Physics for Palaeoclimate Simulations

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1. Introduction

The Weather Research and Forecasting (WRF) model has been used for palaeoclimate simulations by various research groups to simulate European, Asian, and Australian climates. There has, however, never been a description of how to modify the radiation physics to account for the changes in the parameters that describe the Earth's orbit around the Sun. Nor has there been any analysis on how these modifications propagate to the key radiation variables used by WRF: solar declination, solar constant, and cosine of the solar zenith angle; that are used to calculate the incoming solar radiation.

This work presents the necessary modification to the equations used in the WRF radiation physics Fortran code that takes account of the changes in the parameters that describe the Earth's orbital parameters. The Earth's orbital parameters are the eccentricity of the orbit, obliquity, and the longitude of perihelion, which vary over many thousands of years, the so-called "Milankovitch cycles". Despite these long time-scales, even simulations of relatively recent or future periods are also susceptible to issues from the existing calculations in WRF of incoming solar radiation.

The existing calculation in WRF of the solar constant uses an equation that can be traced back to Spencer from 1971[1]. It is unknown for which year (or years) Spencer used for the calculation of his series expansion (panel 2a). Here we present comparisons to 1970 CE, and 1855 CE, which is the first year of the published American Ephemeris and Nautical Almanac. The values for these two years were transcribed from the Almanac and used in the results presented.

The calculation of the cosine of the zenith angle includes an equation for estimating the equation of time. The existing calculation in WRF is also a series expansion which likely approximates modern values (panel 2c).

In this poster we present the existing calculations from the WRF Fortran code and a new calculation that allows for variations in the orbital parameters, for the key components that vary due to changes in these parameters that then propagate through to the incoming solar radiation. These are the eccentricity factor, declination, and the equation of time. These combine to calculate the incoming solar radiation at the top of the model ($SWDTOM$) as:

$$SWDTOM = \frac{S_a}{\rho^2}\cos(z)$$

S_a is the amount of energy received from the Sun perpendicular to the Earth's surface at the distance (a) of the semi-major axis of the Earth's elliptical orbit around the Sun. $\rho = r/a$ is the Earth-Sun distance (r) divided by a. $\cos(z)$ is the cosine of the solar zenith angle, which is itself a function of latitude, declination and the hour angle.

2. Methods

2a. Existing Calculation – SOLCON, DECLIN

The Spencer[1] equation for eccentricity factor used in WRF is:

$$\rho^{-2} = 1.000110 + 0.034221\cos(RJUL) + 0.001280\sin(RJUL) + 0.000719\cos(2RJUL) + 0.000077\sin(2RJUL)$$

Where ρ^{-2} is the Earth-Sun distance (ECCFAC in WRF) and RJUL is the day of the year in radians.

$$SOLCON = \frac{S_a}{\rho^2}$$

Where S_a=1370 W m^{-2}.

$$\delta = \sin^{-1}(\sin(\epsilon)\sin(\lambda))$$

Where δ is the declination (DECLIN in WRF), ϵ (Earth's obliquity) is specified as 23.5°, and λ is the longitude of the Sun from the vernal equinox (March 21), given by:

$$\lambda = \frac{(JULIAN - 80)2\pi}{365}$$

Where $JULIAN$ is the day of the year. Note the default vernal equinox of March 21 (day of year 80) is moved, for consistency, to March 21 at noon (day of year 80.5) in the results presented.

2b. New Calculation – SOLCON, DECLIN

Taking as input the year of the simulation (e.g. 2025), calculate the Earth's orbital parameters, e (eccentricity), ϵ (obliquity), and $\tilde{\omega}$ (longitude of perihelion), from the algorithm described in Berger[2]. This algorithm is not described here, as these values could just as easily be added to module_model_constants.F. The present-day values of the Earth's orbital parameters are: $e = 0.016694$, $\epsilon = 23.44°$, $\tilde{\omega} = 283.32°$.

The new algorithm starts by calculating the mean longitude at the vernal equinox from Berger[2]:

$$\lambda_{m0} = 2\left(\left(\frac{e}{2}+\frac{e^3}{8}\right)(1+\beta)\sin(\tilde{\omega}) - \frac{e^2}{4}\left(\frac{1}{2}+\beta\right)\sin(2\tilde{\omega}) + \frac{e^3}{8}\left(\frac{1}{3}+\beta\right)\sin(3\tilde{\omega})\right)$$

Where β is:

$$\beta = \sqrt{1-e^2}$$

We then calculate λ_m (the mean longitude of the Earth's position) as:

$$\lambda_m = \lambda_{m0} + \frac{(JULIAN - 80.5)2\pi}{365}$$

Where $JULIAN$ is the day of the year and 80.5 is 21 March at noon – the vernal equinox. Then the true longitude of the Earth's position is calculated as:

$$\lambda = \lambda_m + e\left(2\sin(\lambda_m) + e\left(\frac{5}{4}\sin(2\lambda_m) + e\left(\frac{13}{12}\sin(3\lambda_m) - \frac{1}{4}\sin(\lambda_m)\right)\right)\right)$$

The last step is to calculate the eccentricity factor ρ^{-2}:

$$\rho^{-2} = \frac{1+e\cos(\lambda-\tilde{\omega})}{1-e^2}$$

From which the algorithm returns the same variable (SOLCON) as the existing equation (panel 2a):

$$SOLCON = \frac{S_a}{\rho^2}$$

And the declination (DECLIN)

$$\delta = \sin^{-1}(\sin(\epsilon)\sin(\lambda))$$

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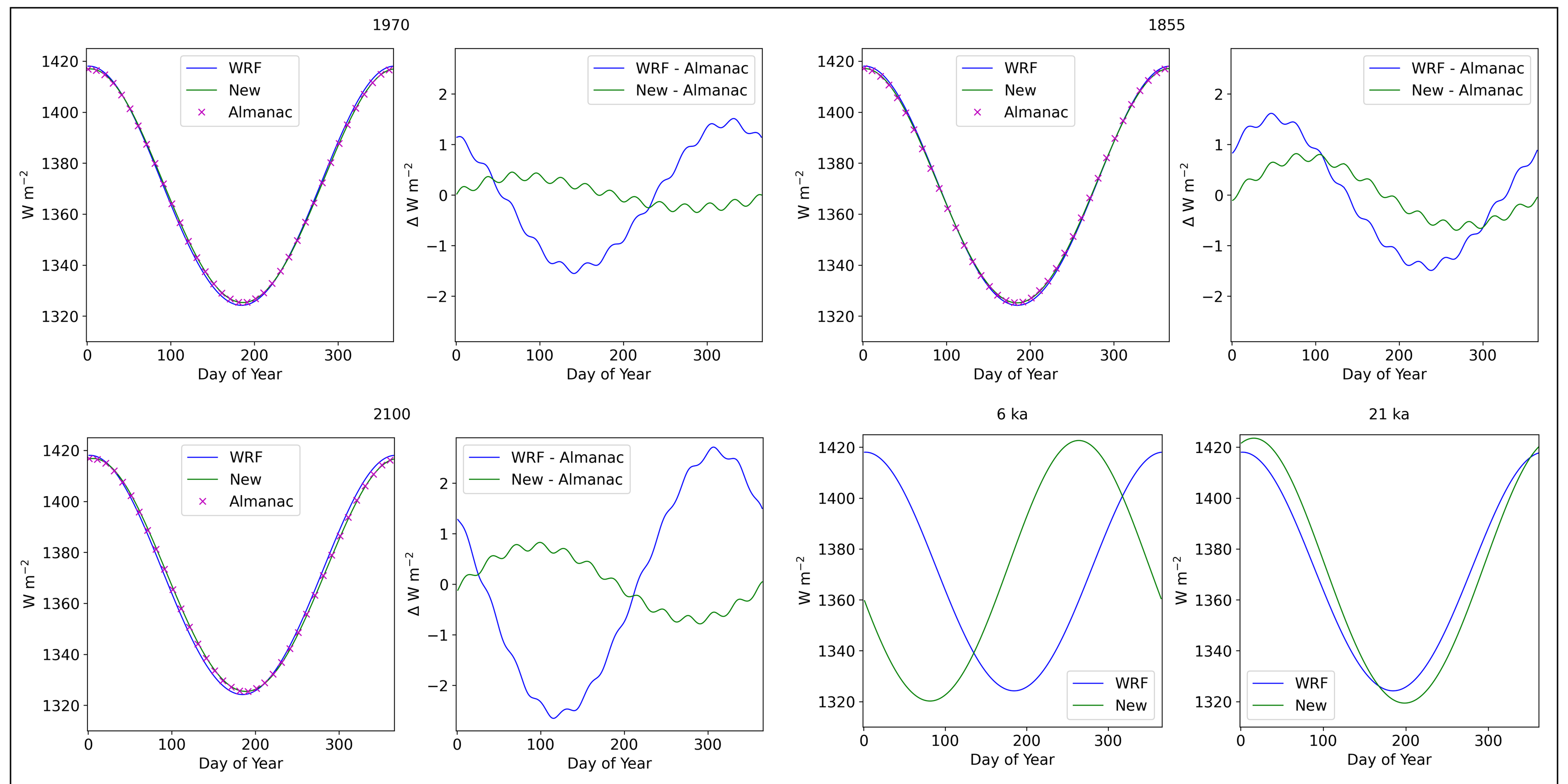

Figure 1. The eccentricity factor for 1970 CE (top left), 1855 CE (top right), 2100 CE (bottom left), and 6 ka and 21 ka (bottom right). The calculations are Spencers equation used in WRF (panel 2a) "WRF" in blue, the new calculation using Berger's orbital parameters (panel 2b) "New" in green, and the Earth-Sun distance from The American Ephemeris and Nautical Almanac "Almanac" purple crosses (not available for 2100, 6 ka, or 21 ka); for 2100 the "Almanac" values are taken from the JPL Horizons on-line ephemeris system, multiplied by the Sa=1370. The left panel shows the evolution through the year. The right panel (excluding 6 ka and 21 ka) shows the difference between the two algorithms, WRF or New, and the values from the Almanac. A vernal equinox of March 21 at noon is used in both algorithms for consistency.

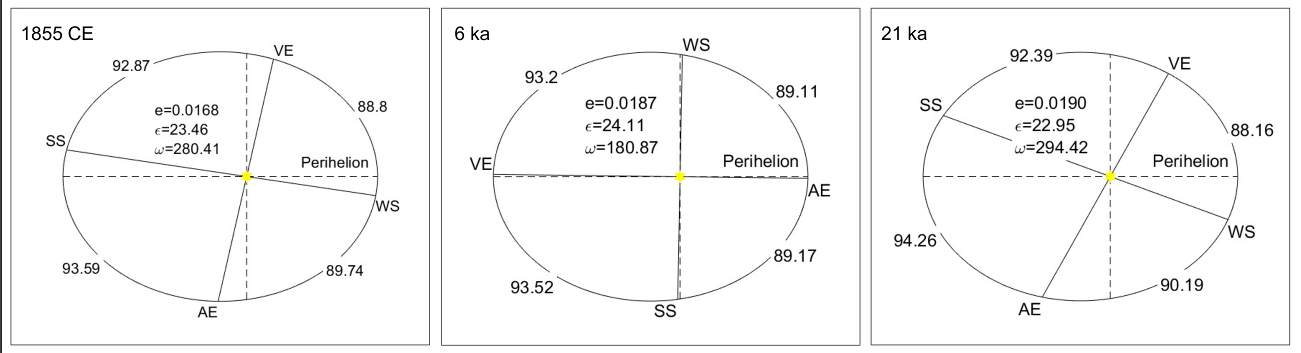

Figure 2. The orbital parameters for 1855 CE (left), 6 ka (middle), and 21 ka (right). e is eccentricity, ϵ is obliquity, and ω is the longitude of perihelion. VE is the vernal equinox, SS summer solstice, AE autumnal equinox, and WS winter solstice. The season length in days is shown on the orbit.

2c. Existing Calculation – COSZEN

The cosine of the solar zenith angle in WRF is:

$$\cos(z) = \sin(\phi_{i,j})\sin(\delta) + \cos(\phi_{i,j})\cos(\delta)\cos(h)$$

Where $\phi_{i,j}$ is the latitude of the location, δ is the declination, and h is the hour angle given by:

$$h = 15\left[\left(gmt + \frac{t+\Delta t}{60} + \frac{\lambda_{i,j}}{15}\right) - 12\right]\frac{\pi}{180}$$

Where t is the local time of day, gmt is Greenwich Mean Time, $\lambda_{i,j}$ is the longitude of the location, and Δt is the equation of time given by:

$$\Delta t = [0.000075 + 0.001868\cos(da) - 0.032077\sin(da) - 0.014615\cos(2da) - 0.04089\sin(2da)]229.18$$

Where:

$$da = \frac{2\pi(JULIAN - 1)}{365}.$$

Where $JULIAN$ is the day of the year.

2d. New Calculation – COSZEN

To calculate the cosine of the zenith angle, we need to account for changes to the equation of time from the timing of perihelion. To do this we first calculate λ_{m0} from Berger[2] (see panel 2b). We then calculate the mean anomaly of the Earth's orbit:

$$M = (\lambda_{m0} + 2\pi - \tilde{\omega}) + \frac{2\pi(JULIAN - 80.5)}{365.2596358}$$

Where 365.2596358 is the anomalistic year, $JULIAN$ is the day of the year, and $\tilde{\omega}$ is the longitude of perihelion (see panel 2b).

The 2nd order equation of time is then given by:

$$\Delta t = -2e\left(\frac{1440}{2\pi}\right)\sin(M) + y\left(\frac{1440}{2\pi}\right)\sin(2M+2\tilde{\omega}) - \frac{5}{4}e^2\left(\frac{1440}{2\pi}\right)\sin(2M)$$
$$+4ey\left(\frac{1440}{2\pi}\right)\sin(M)\cos(2M+2\tilde{\omega}) - \frac{y^2}{2}\left(\frac{1440}{2\pi}\right)\sin(4M+4\tilde{\omega})$$

Where y is:

$$y = \tan^2\left(\frac{\epsilon}{2}\right)$$

Δt here is then used to calculate the hour angle and finally the cosine of the zenith angle as per panel 2c.

Acknowledgements

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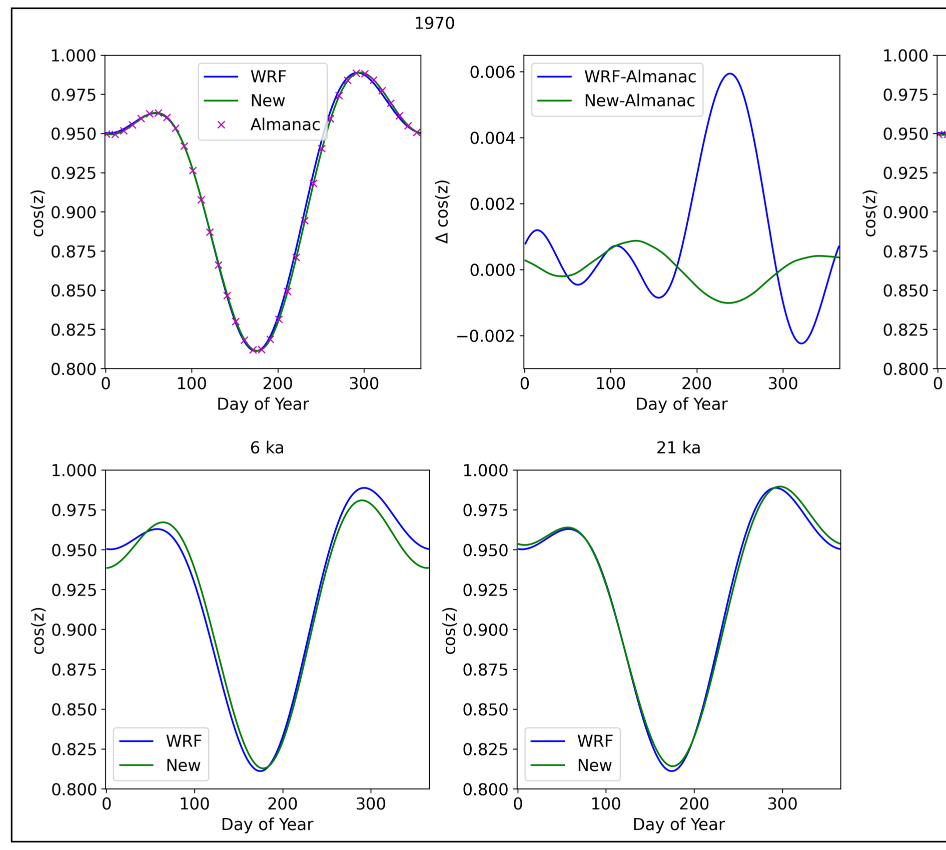

Figure 3. The cosine of the solar zenith angle (cos(z)) for 1970 CE (top left), 1855 CE (top right), and 6 ka and 21 ka (bottom left), for latitude = 10° S and longitude = 130° E. The calculations used are the existing calculation in WRF (panel 2c) "WRF" in blue, the new calculation using Berger's orbital parameters (panel 2d) "New" in green, and values from The American Ephemeris and Nautical Almanac "Almanac" purple crosses (not available for 6 ka and 21 ka). For 1970 CE and 1855CE, the right panel shows the difference between the two algorithms, WRF or New, and the values from the Almanac.

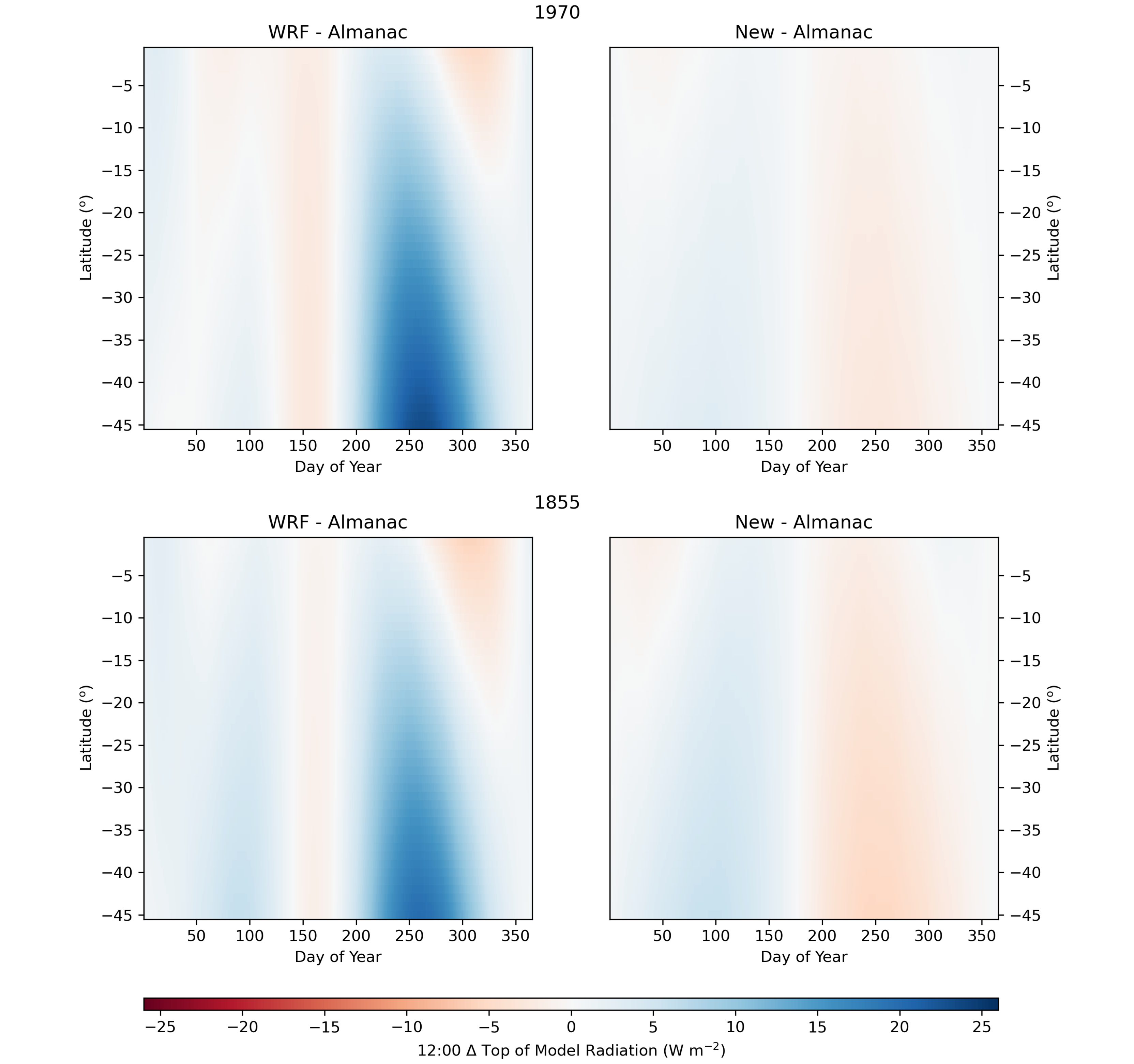

Figure 4. The Top of the Model incoming radiation (W m^{-2}) at longitude 130° E at 12:00 local time, for 1970 CE (top) and 1855 CE (bottom). The left panel shows the difference between the WRF calculation (panels 2a & 2c) and the values from The American Ephemeris and Nautical Almanac "Almanac". The right panel shows the difference between the new calculation (panels 2b & 2d) and the "Almanac".

3. Results

- The eccentricity factor is less accurate than the new calculation, even for periods close to 1970 CE. The inaccuracy is most evident when the timing of perihelion is further from present day values (Figures 1 & 2).
- The cosine of the solar zenith angle (Figure 3) contributes the largest component to the incoming radiation anomalies (Figure 4).
- The changes in the true longitude of the Earth's position (λ) which propagate through solar declination (δ) to the cosine of the solar zenith angle is the largest component of the anomalies between the algorithms.
- The new calculation provides slightly more accurate estimations of incoming solar radiation for present-day simulations but critically allows for simulations with Earth orbital parameters that are not near present-day conditions.

References

1 Spencer, J. W. Fourier series representation of the position of the sun. *Search.* **2 (5)** 172 (1971).

2 Berger, A. Long-term variations of daily insolation and Quaternary climatic changes. *J. Atmos. Sci.* **35**, 2362–2367 (1978).